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## RESEARCH LETTER

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## Key Points:

- Reassessment of Abbot sector mass balance using CryoSat-2-derived ice thicknesses provides better agreement with other techniques
- Discrepancies in input-output method estimates primarily due to overestimation of ice thickness for these regions in previous products
- Velocity increases and negative elevation rates at the Getz grounding line indicate dynamic imbalance and probable grounding line retreat

## Supporting Information:

- Supporting Information S1

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## Mass balance reassessment of glaciers draining into the Abbot and Getz Ice Shelves of West Antarctica

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**Abstract** We present a reassessment of input-output method ice mass budget estimates for the Abbot and Getz regions of West Antarctica using CryoSat-2-derived ice thickness estimates. The mass budget is  $8 \pm 6 \text{ Gt yr}^{-1}$  and  $5 \pm 17 \text{ Gt yr}^{-1}$  for the Abbot and Getz sectors, respectively, for the period 2006–2008. Over the Abbot region, our results resolve a previous discrepancy with elevation rates from altimetry, due to a previous 30% overestimation of ice thickness. For the Getz sector, our results are at the more positive bound of estimates from other techniques. Grounding line velocity increases up to 20% between 2007 and 2014 alongside mean elevation rates of  $-0.67 \pm 0.13 \text{ m yr}^{-1}$  between 2010 and 2013 indicate the onset of a dynamic thinning signal. Mean snowfall trends of  $-0.33 \text{ m yr}^{-1}$  water equivalent since 2006 indicate recent mass trends are driven by both ice dynamics and surface processes.

**Plain Language Summary** There are large differences in mass balance estimates (the net loss or gain of ice mass) from independent techniques for glaciers draining into the Abbot and Getz Ice Shelves of West Antarctica. This is believed to be primarily due to previous uncertainties in the knowledge of ice thickness in these regions at the grounding line (the point where the ice sheet detaches from the bedrock and begins to float). We use new higher-accuracy ice thickness measurements derived from ESA's CryoSat-2 satellite to reassess the mass balance for these regions for the 2006–2008 period. Our results provide better agreement with other techniques and resolve outstanding discrepancies over the Abbot region in particular. We also find that grounding line retreat, a key indicator of ice sheet imbalance, has likely to have been occurring over the Getz region since this period. Our results demonstrate the ability for the satellite to more accurately calculate the mass loss from these regions and better constrain their subsequent contribution to sea level rise.

## 1. Introduction

Accurate assessments of Antarctic mass balance are needed to understand the ice sheet's response to climate change and the subsequent contribution to sea level rise. The West Antarctic Ice Sheet (WAIS), in particular, has undergone rapid changes in mass balance over the last two decades: with substantial increases in ice velocity [Mouginot *et al.*, 2014], widespread inland ice sheet thinning [Helm *et al.*, 2014; McMillan *et al.*, 2014], and grounding line retreat [Christie *et al.*, 2016; Scheuchl *et al.*, 2016].

Ice sheet mass balance can be assessed using three independent techniques: ice sheet elevation changes from altimetry [Zwally *et al.*, 2005; McMillan *et al.*, 2014; Wouters *et al.*, 2015], changes in the Earth's gravity field from ice mass fluctuations [Gunter *et al.*, 2009; Velicogna, 2009; Sasgen *et al.*, 2013], and differences in surface mass balance (SMB) compared to grounding line flux (GLF), known as the input-output method (IOM) [Rignot *et al.*, 2008, 2011a]. Each technique has varying spatiotemporal resolutions and requires numerical model outputs to constrain unobserved processes, which introduce unknown biases into the results [Zammit-Mangion *et al.*, 2015a; Martín-Español *et al.*, 2016]. A Bayesian statistical hierarchical framework has also been developed within a project called RATES [Zammit-Mangion *et al.*, 2014, 2015a, 2015b; Martín-Español *et al.*, 2016] and is an alternative approach to the three methods described above. While attempts have been made to combine results from different techniques by taking the arithmetic mean of multiple estimates [Shepherd *et al.*, 2012], understanding and reducing the major sources of uncertainty in each method is the best way to produce robust and accurate mass balance estimates.

An advantage of the IOM approach is its ability to determine mass balance at an individual basin scale and partition contributions by surface-driven (variations in snowfall) and ice dynamic processes. Large differences exist between IOM estimates and other techniques for the Getz and Abbot regions of West

Antarctica [Sasgen *et al.*, 2010; Shepherd *et al.*, 2012]. This is particularly apparent in the Abbot sector where there are contrasting positive ice sheet elevation rates and negative IOM mass budget estimates [Rignot *et al.*, 2008; Flament and Remy, 2012; Pritchard *et al.*, 2012]. This inconsistency between the different methods is primarily thought to be due to lack of ice thickness observations from ice-penetrating radar (IPR) data in these regions [Sasgen *et al.*, 2010; Martín-Español *et al.*, 2016]. In areas of sparse observational coverage, surface elevations from ERS-1 radar altimetry combined with the assumption of hydrostatic equilibrium have been used to provide estimates of ice thickness [Griggs and Bamber, 2011]. However, conventional satellite radar altimetry (prior to CryoSat-2) suffered from poor coverage near the grounding line due to complex topography creating “loss of lock” and off-ranging issues. Consequently, there were relatively large errors in the ERS-1-derived thickness data, which required manual adjustments of up to 100 m to ensure consistency with IPR observations during the creation of the most recent ice thickness compilation for the continent, Bedmap2 [Fretwell *et al.*, 2013].

The synthetic aperture radar interferometric mode and orbital characteristics of CryoSat-2 (hereafter referred to as CS2) [Wingham *et al.*, 2006b] have overcome many of the limitations of previous radar altimetry missions. Consequently, the accuracy of ice thickness data, derived from surface elevations, has greatly improved in the vicinity of the grounding line [Chuter and Bamber, 2015]. This improved accuracy provides the opportunity to reassess the mass balance of sectors where IPR data are unavailable and altimetry-derived thickness was used instead. Here we examine the Getz and Abbot sectors to investigate the inconsistencies between methodologies and reduce this source of uncertainty in the IOM method.

## 2. Data and Methods

Contemporary ice shelf thickness measurements (2013–2014) are derived from CS2 baseline B L2i data using the same methodology employed to create the new continental data set [Chuter and Bamber, 2015]. A more detailed discussion of the methodology can be found in the supporting information [Bamber and Bentley, 1994; Fricker *et al.*, 2001; Knudsen and Andersen, 2012; Förste *et al.*, 2014]. Validation of the CS2-derived product with elevation measurements from ICESat shows approximately a threefold and fivefold reduction in noise within 10 km of the grounding line for the Abbot and Getz Ice Shelves (Tables S1 and S2) respectively, compared to the earlier (pre-CS2) product [Griggs and Bamber, 2011]. To use contemporary CS2-derived ice thickness measurements to reassess mass balance estimates for the 2006–2008 epoch, an adjustment to the CS2 ice thickness product was made using 18 year observations of ice shelf thickness change ( $dZ/dt$ ) at a 27 km spatial resolution [Paolo *et al.*, 2015]. A third-order polynomial fit was applied to the 18 year time series to extend the record to the 2013–2014 epoch of the CS2 ice shelf thickness measurements, as the  $dZ/dt$  time series only extends until the end of 2011 (Figures S1 and S2). By correcting for  $dZ/dt$  between 2006 and 2013, it allows for estimates of grounding line discharge to be made predating CS2. Uncorrected ice thicknesses from Bedmap2 are also used for thickness comparison purposes between studies [Fretwell *et al.*, 2013].

Velocities for the 2006–2008 time period were taken from the MEaSURES data set [Rignot *et al.*, 2011b], with measurements for the Getz and Abbot regions derived predominantly from feature and speckle tracking of 2006–2008 ALOS PALSAR data (ERS-1/2 is used to fill data gaps in some localities over the Abbot region). The launch of Landsat-8 with its improved radiometric resolution and higher geolocation accuracy allowed for wide area ice velocity mapping using the Pycorr software, a normalized cross-correlation pixel matching algorithm [Fahnestock *et al.*, 2015]. The result is a contemporary composite velocity product which provides near complete spatial coverage with accuracies comparable to interferometric synthetic aperture radar (InSAR) techniques.

Grounding line locations were provided from a composite of previous data sets [Depoorter *et al.*, 2013b], with preference given to delineations from ICESat and InSAR techniques (the Antarctic Surface Accumulation and Ice Discharge product being used to fill in data gaps) [Bindshadler *et al.*, 2011]. Therefore, the grounding line is comprised mostly from InSAR data from 1992 to 2000 and 1996 for the Abbot and Getz, respectively (more modern ICESat grounding line delineations from 2003 to 2009 were used over these regions where available). Only minor grounding line retreat has occurred between 1990 and 2015 over the Abbot region [Christie *et al.*, 2016]. The use of grounding line positions from 1992 introduces, therefore, minimal errors into grounding line flux calculations. Basin discharge is determined through integration of the CS2-derived ice shelf thickness values with ice velocity at the grounding line.

Total mass balance is determined for each drainage basin by computing the difference between SMB and GLF. Drainage basin delineation for calculating SMB is calculated from ice sheet interior velocity observations and modeling [Depoorter *et al.*, 2013a]. SMB for the 2006–2008 epoch is calculated using the RACMO 2.3 climate model, run at 27 km resolution, and forced at its boundaries by European Centre for Medium-Range Weather Forecasts ERA interim reanalysis data [van Wessem *et al.*, 2014]. While other studies have used SMB values from long temporal baselines to reduce interannual variability [Rignot *et al.*, 2008; Depoorter *et al.*, 2013a], this prevents direct comparison with other techniques which record mass change on shorter time scales. For the coastal regions of the WAIS, a conservative error estimate of 20% is used for SMB model uncertainty [van Wessem *et al.*, 2014; Wouters *et al.*, 2015]. To determine annual trends in SMB from 2006 to the present day, model anomalies are calculated with respect to a 26 year baseline period between 1979 and 2005.

### 3. Results

To assess the ability of the CS2-derived ice thickness product to accurately calculate GLF, we used a test case of glaciers draining into the Amery Ice Shelf due to the extensive coverage of the region by IPR campaigns since 1962 [Yu *et al.*, 2010]. Using CS2-derived ice thickness estimates results in a GLF of  $63 \pm 5 \text{ Gt yr}^{-1}$ . This is almost identical to the  $64.3 \pm 3.2 \text{ Gt yr}^{-1}$  produced when using the original IPR measurements for ice thickness (as opposed to a gridded product such as Bedmap2) [Yu *et al.*, 2010]. Some of the IPR measurements predate the observational record of ice shelf thickness change, making it not possible to correct for this. We believe, however, that the effect of this is likely minimal as the ice shelf has been close to balance for at least the last two decades [Paolo *et al.*, 2015]. This demonstrates the ability of CS2-derived ice thicknesses to accurately calculate ice discharge in regions where no IPR data exist.

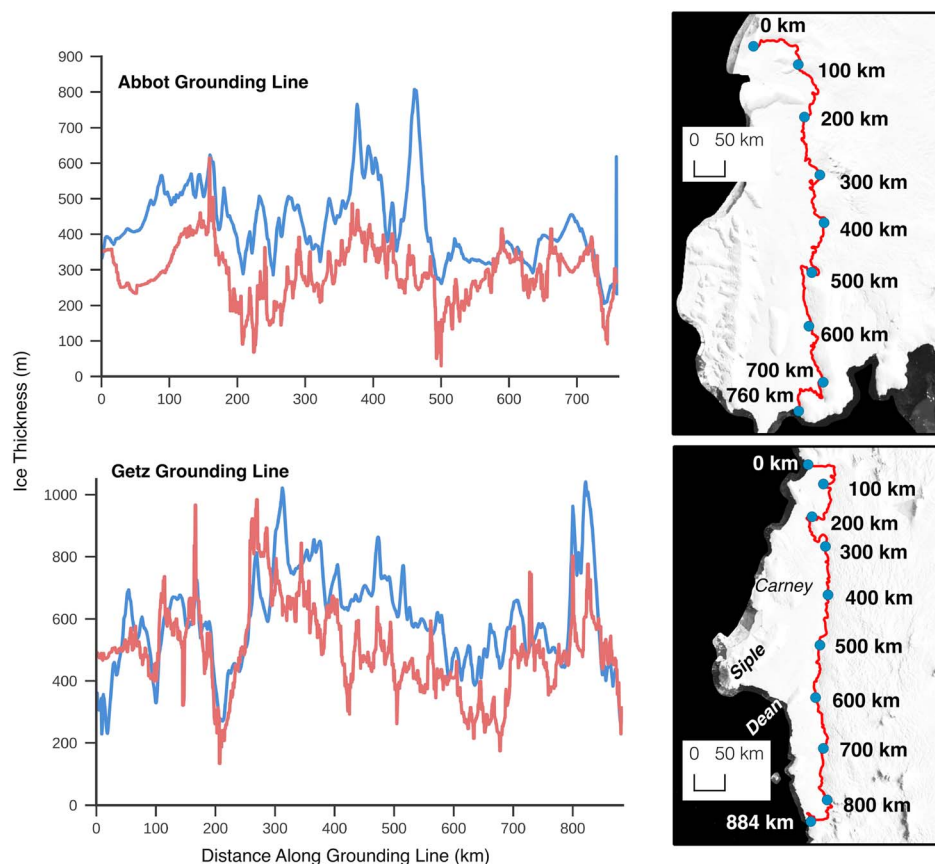
#### 3.1. Abbot Sector

For glaciers in the Bellingshausen Sea Sector draining into the Abbot Ice Shelf, grounding line ice thickness measurements derived from CS2 data are systematically thinner than those from the Bedmap2 product (Figure 1) by 30%. The grounding zone has sparse IPR coverage, and therefore, Bedmap2 thickness values at this location are based on the ERS-1 ice shelf thickness data product, giving the grounding line thickness a timestamp of 1995 [Griggs and Bamber, 2011]. Despite the 20 year temporal difference between the measurements, ice thickness differences far exceed the mean  $1.5 \pm 0.9 \text{ m}$  per decade rate of ice shelf thinning [Paolo *et al.*, 2015]. We conclude that the differences in thicknesses at the grounding line are due to the increased coverage and accuracy that CS2 offers within the grounding zone of this region [Chuter and Bamber, 2015].

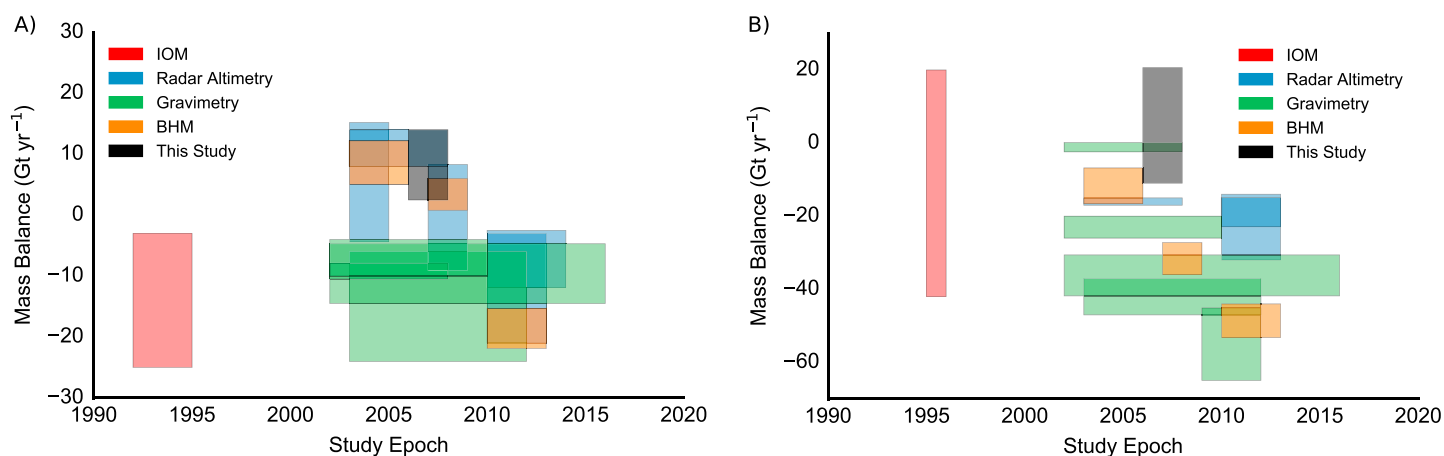
After adjusting the CS2-derived ice thickness measurements to the 2006–2008 epoch, the GLF is reduced from  $31 \pm 10 \text{ Gt yr}^{-1}$  to  $18 \pm 3 \text{ Gt yr}^{-1}$  for the Abbot sector. When combined with a mean basin-integrated SMB of  $26 \pm 5 \text{ Gt yr}^{-1}$ , this results in an overall mass budget of  $-5 \pm 10 \text{ Gt yr}^{-1}$  and  $+8 \pm 6 \text{ Gt yr}^{-1}$  (Figure 2a) when using Bedmap2 and CS2 ice thickness estimates, respectively. From the 2006–2008 period to the present day, there has been little increase in ice velocity at the grounding line and no discernible trend in basin SMB anomalies over the last decade (Figure S3). Evidence of minor grounding line retreat over some sections of the Abbot basin [Christie *et al.*, 2016] suggests the basin may have progressed to a less positive mass balance state from 2008 to the present day.

#### 3.2. Getz Sector

At the grounding line of the Getz Ice Shelf, CS2 ice thicknesses are reduced by 16.5% compared to Bedmap2 (Figure 1). While Bedmap2 ice thickness at the Getz grounding line is derived from the previous ERS-1 product [Griggs and Bamber, 2011], a manual adjustment to reduce ice thickness by 48 m was made to provide better agreement with IPR data from a 2009/2010 Operation Ice Bridge flight line 5–10 km inland of the grounding line [Fretwell *et al.*, 2013]. Strong basal melt rates over the Getz Ice Shelf of up to  $66.5 \pm 9 \text{ m}$  per decade [Paolo *et al.*, 2015] may explain some of the thickness disparities between the data sets. However, determining the exact contribution of basal melt to differences between the thickness estimates is difficult due to the difference in acquisition dates between the data sources used in Bedmap2 and the manual adjustments that have been made. Additionally, a comparison between an Operation Ice Bridge (OIB) flight line from 2014 to the CS2 ice thickness from 2014 (Figure S7) indicates a slight underestimation of ice thickness in the CS2 product (see section 4 for further explanation).

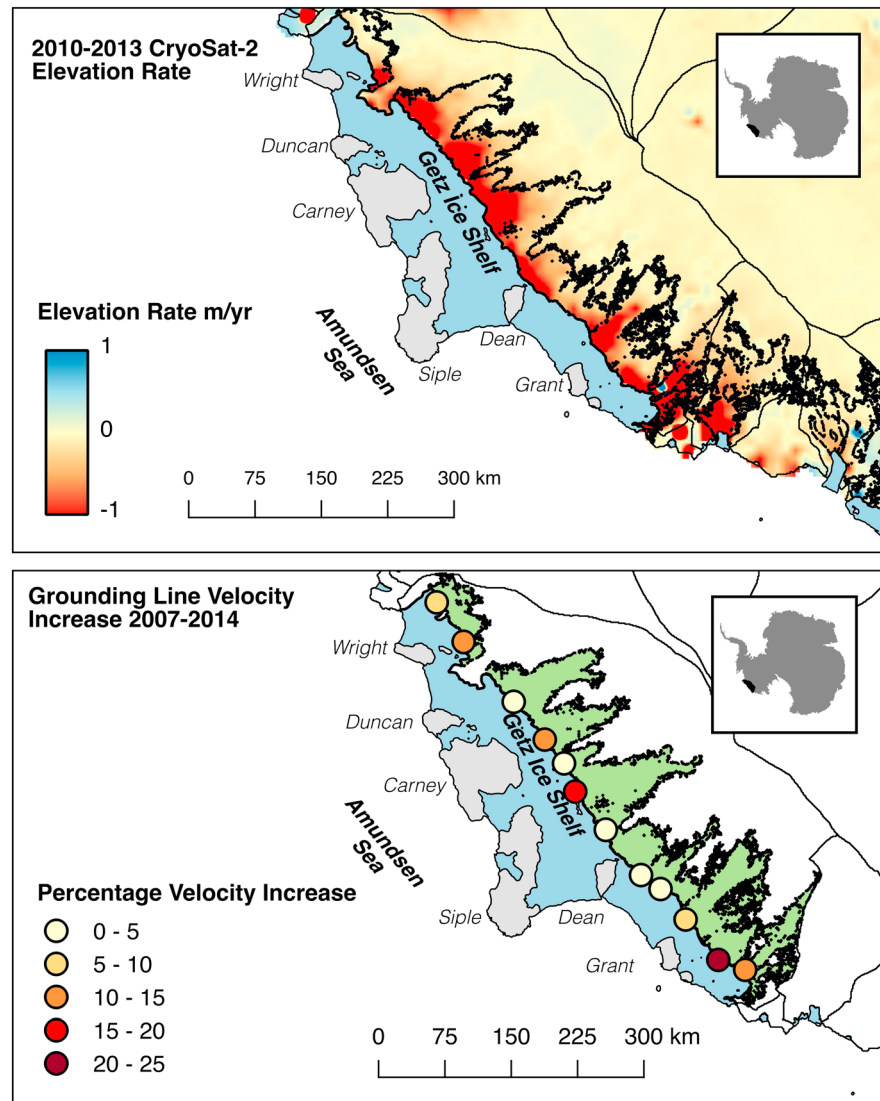


**Figure 1.** Ice thickness comparison for the Getz and Abbot Ice Shelves grounding lines for the Bedmap2 data product (blue) and the 2007 temporally adjusted CS2 product (red). Inset maps show the corresponding locations along the grounding line to the thickness comparison plots. There is a mean thickness difference of 30% and 16.5% for the Abbot and Getz grounding lines, respectively. On the inset maps, the grounding line is shown in red [Depoorter et al., 2013b] and the blue circles represent 100 km sectors along the grounding line. Data are overlain on the Moderate Resolution Imaging Spectroradiometer Mosaic of Antarctica [Haran et al., 2014].



**Figure 2.** Comparison of mass balance studies for multiple techniques from 1990 to the present day for (a) the Bellingshausen Sea Sector and (b) Getz region. The reassessed mass budget estimate presented in this paper is shown in black. The individual studies and mass balance figures are presented in Table S3 and Table S4 of the supporting information for the Bellingshausen Sea and Getz Sectors, respectively [Rignot et al., 2008; Sasgen et al., 2010, 2013; King et al., 2012; Bouman et al., 2014; McMillan et al., 2014; Wouters et al., 2015; Zwally et al., 2015; Groh and Horwath, 2016; Martín-Español et al., 2016].





**Figure 3.** (top) Elevation rates from CS2 for the 2010–2013 period, following the method of *Wouters et al.* [2015]. The largest negative elevation rates are located near the grounding line and within areas where ice velocity is  $>50 \text{ m yr}^{-1}$  (black dashed line). (bottom) Changes in ice velocity between the MEaSUREs product [*Rignot et al.*, 2011b] from 2007 and the new Landsat-8 product from 2014 [*Fahnestock et al.*, 2015]. The circles represent changes in velocity magnitude between the time periods for each section of the grounding line. The green region represents areas of high ice velocity ( $>50 \text{ m yr}^{-1}$ ).

Using ice shelf thickness measurements derived from CS2 to calculate the Getz region mass balance for the 2006–2008 epoch gives a grounding line discharge and mass budget estimate of  $64 \pm 8 \text{ Gt yr}^{-1}$  and  $+5 \pm 17 \text{ Gt yr}^{-1}$  (Figure 2b), respectively (with a SMB of  $69 \pm 14 \text{ Gt yr}^{-1}$ ). These results are more positive than a previous IOM estimate which had a grounding line flux and mass budget of  $98 \pm 18 \text{ Gt yr}^{-1}$  and  $-11 \pm 31 \text{ Gt yr}^{-1}$ , respectively [*Rignot et al.*, 2008]. From the 2006–2008 epoch to the present day there have been modest increases in ice velocity of up to 20% at some locations along the grounding line (Figure 3). Additionally, analysis of SMB anomalies from 2013 to 2015 with respect to a 1979 to 2005 baseline shows mean negative trends of  $-0.33 \text{ m yr}^{-1}$  (Figure S4) across the basin, reaching rates of up to  $-0.80 \text{ m yr}^{-1}$  near the grounding line.

#### 4. Discussion

The new IOM mass balance estimate for glaciers draining into the Abbot Ice Shelf provides consistency with estimates derived from radar altimetry for the same time period [*Wouters et al.*, 2015; *Zwally et al.*, 2015] and

positive basin  $dh/dt$  elevation rates from ICESat and Envisat [Pritchard *et al.*, 2009; Flament and Remy, 2012]. The excellent agreement between our IOM estimate ( $+8 \pm 6 \text{ Gt yr}^{-1}$ ) and results from the RATES project ( $+9 \pm 1 \text{ Gt yr}^{-1}$ ) suggests that the likely cause of the earlier negative IOM-derived mass balance estimate was due to a positive bias in the ice thickness product used. While IPR data are sparse over this shelf, previous comparisons with OIB data show that Bedmap2 ice thicknesses were overestimated by  $\sim 15\%$  [Cochran *et al.*, 2014], agreeing with the comparisons presented here. Limited ERS-1 coverage near the grounding line and its bias toward higher elevation measurements (when compared to ICESat) in this region [Griggs and Bamber, 2011] would explain why the thickness differences presented here are larger than those reported over the rest of the shelf.

The mass budget estimate for the Abbot sector is at the more positive bound of the range of results from other techniques (Figure 2a), which we attribute primarily to the differences in drainage basin area used between studies. Other studies shown in Figure 2a include the Wesnet, Williams, Fox, and Ferrigno Ice Streams in their basin extents for this region [Shepherd *et al.*, 2012; Zwally *et al.*, 2012; Sasgen *et al.*, 2013]. Results from the RATES project show a mass balance of  $-3 \pm 1 \text{ Gt yr}^{-1}$  for the Fox and Ferrigno and  $0 \pm 1 \text{ Gt yr}^{-1}$  for the Wesnet and Williams sectors for the 2006–2008 period (Figure S5). As a result, the mass budget results for the Abbot sector presented in this study would be expected to be approximately  $3 \text{ Gt yr}^{-1}$  more positive than the comparison studies used in Figure 2a due to the exclusion of these regions in our calculations.

Minimal increases in velocity between 2007 and the present day in combination with minor grounding line retreat of up to 0.77 km between 1990 and 2015 [Christie *et al.*, 2016] for the Abbot sector indicate that these smaller ice streams have been the driver of the increases in negative mass trends for this region over the last decade. This is consistent with observed CS2 dynamic thinning trends in the region [Wouters *et al.*, 2015] and ice dynamic trends from RATES (Figure S5).

Our work shows that previous ice thickness data sets were biased in a variety of ways. At the Getz grounding line, the manual thickness reduction adjustment of 48 m applied when integrating ERS-1 derived ice thicknesses into Bedmap2 [Fretwell *et al.*, 2013] indicates a bias toward thicker ice and larger grounding line discharge when using the previous ERS-1 ice shelf thickness product [Griggs and Bamber, 2011]. Comparisons of the ERS-1 DEM used to calculate ice shelf thickness with ICESat near the grounding line showed a bias of approximately 9 m (80 m ice thickness) toward thicker ice [Griggs and Bamber, 2011]. This suggests that the correction made when integrating the product into Bedmap2 may not have fully accounted for the bias. Additionally, ice shelf cavity geometries derived from Bedmap2 in this region typically needed manual adjustments within the vicinity of the grounding line to compensate for negative water column thicknesses, which can be attributed to poorly resolved bathymetry and overestimations of ice thickness [Timmerman *et al.*, 2010; Fretwell *et al.*, 2013]. Comparisons with IPR data at four points along the grounding line (three of which were incorporated into the Bedmap2 product) show that in every case the Bedmap2 thickness measurements are greater than that of IPR (in one case the IPR ice thickness measurement is approximately 23% lower than that from the gridded product). A possible explanation for this difference could be the interpolation scheme used in this region of complex surface and basal topography.

Our reassessed mass budget estimate for the Getz region is slightly positive for the 2006–2008 period. It is within the  $1\sigma$  error bound of the arithmetic mean of radar altimetry studies between 1992 and 2011 [Shepherd *et al.*, 2012] and in agreement with a gravimetry study from a similar time period (Figure 2b) [Sasgen *et al.*, 2010]. Mass balance estimates from RATES of  $-12 \pm 4 \text{ Gt yr}^{-1}$  for the 2006–2008 period, using the same basin extent as our mass budget estimate, are at the more negative end of our mass budget uncertainty bounds. The RATES results show the basin to be in a slight state of imbalance in 2006 ( $-7 \pm 4 \text{ Gt yr}^{-1}$ ) and 2007 ( $-2 \pm 4 \text{ Gt yr}^{-1}$ ), with a large mass loss in 2008 ( $-27 \pm 4 \text{ Gt yr}^{-1}$ ) (Figure S6). As a result, the magnitude of the 2006–2008 mean imbalance from RATES is primarily due to mass losses occurring in the last year of our study epoch. The results presented here contrast from the previous 1996 IOM estimate showing the Getz region to be in a negative mass balance state [Rignot *et al.*, 2008], which appeared to conflict with positive elevation rates over the drainage basin from 1992 to 2003 [Wingham *et al.*, 2006a] from satellite altimetry. Our new estimate therefore suggests that ice thickness at the grounding line was a major contributor to discrepancies between IOM and other techniques.

While our study focuses on the Getz sector, other studies shown in Figure 2b include the Hull, Land, and Nickerson sectors in their basin delineations. Results from the RATES project for these other regions for the 2006–2008 period (Figure S6 and Table S5) indicate that our mass budget estimate is approximately  $2 \text{ Gt yr}^{-1}$  more positive than other studies in Figure 2b due to differences in basin extent alone. The minimal effect these other sectors have on our mass budget estimate indicates that the Getz sector is the primary driver of mass loss in the region.

A thickness comparison made between a 2014 OIB flight line [Leuschen *et al.*, 2010] across the Getz Ice Shelf (Figure S7) shows a median 57 m underestimation in ice thickness in the CS2 product. This bias could be due penetration effects of the radar signal [Wang *et al.*, 2015] and the firn depth correction used in the ice thickness calculation. The CS2 ice shelf freeboard has a small bias of about 2–3 m (equivalent to 18–27 m in thickness) toward lower elevations near the grounding line compared to ICESat data (Table S2). However, the use of modeled values to correct for the variable density layer of the firn column is one of the major sources of uncertainty when calculating hydrostatically derived ice thickness, with firn air content exhibiting significant variations along the grounding line [van den Broeke *et al.*, 2008]. This is partly due to the 27 km model resolution not being able to fully resolve firn air depth in regions of complex topography [Ligtenberg *et al.*, 2014; Lenaerts *et al.*, 2016]. In regions of convergent ice flow, longitudinal compression of the ice column will likely result in an over prediction of firn air depth [Bamber and Bentley, 1994]. This is, to date, an effect that is not included in firn densification models. For a thorough accuracy assessment of the derived ice shelf thicknesses, however, more extensive IPR coverage is required. The positive bias present in the previous ERS-1-derived ice shelf freeboard [Griggs and Bamber, 2011] may have partly or fully compensated for areas where the modeled firn air depth was overestimated.

The presence of a small bias toward thinner ice across this flight line suggests the true mass budget value lies toward the more negative end of our uncertainty bounds (which would provide closer agreement with the results from other studies). This highlights the need for improved firn air content estimates when determining grounding line discharge in regions with poor observational coverage (approximately 30% of the Antarctic grounding line) [Depoorter *et al.*, 2013a]. Additionally, the 27 km resolution of the ice shelf thickness change correction applied to calculate mass balance for the 2006–2008 epoch may not fully capture localized enhanced basal melt occurring near the grounding line.

Since the 2006–2008 period there have been large discrepancies in mass balance estimates between techniques for the Getz region, with the largest observed negative imbalance of  $-55 \pm 9 \text{ Gt yr}^{-1}$  coming from gravimetry observations from 2009 to 2012 (Figure 2b) [Bouman *et al.*, 2014]. Additionally, gravimetry measurements show a statistically significant acceleration in mass loss for the region of  $6 \text{ Gt yr}^{-2}$  from 2002 to 2012 [Sasgen *et al.*, 2013]. There are large discrepancies between altimetry and gravimetry mass balance estimates for the 2010–2013 period for the Getz region, with CS2 altimetry mass loss almost half as negative as gravimetry [McMillan *et al.*, 2014]. The tendency for gravimetry to produce more negative results has been seen in previous comparison studies with altimetry [Gunter *et al.*, 2009] and could be due to signal leakage from the neighboring Smith and Pope glaciers, which have undergone rapid grounding line retreat driven by oceanic forcing [Khazendar *et al.*, 2016; Scheuchl *et al.*, 2016]. It may also be due the fact that Gravity Recovery and Climate Experiment results implicitly account for grounding line retreat, while altimetry and IOM need an explicit correction to be applied (discussed below). As far as we are aware, that has not been done in the case of altimetry-derived estimates.

Observations of ice sheet elevation rates and velocity since the 2006–2008 epoch of our mass balance recalculation show changes in ice dynamics for the Getz region of West Antarctica. In areas of high-surface ice velocity ( $>50 \text{ m yr}^{-1}$ ), there has been a mean thinning rate of  $-0.67 \pm 0.13 \text{ m yr}^{-1}$  from CS2 (Figure 3) between 2010 and 2013. This is a marked increase on the  $-0.23 \text{ m yr}^{-1}$  elevation rate from ICESat for the 2003–2007 period [Pritchard *et al.*, 2009]. Coupling these trends in surface elevation rates with increases in velocity at the grounding line of up to 20% between 2007 and 2014 (Figure 3) implies dynamic thinning in the region and the likelihood of grounding line retreat over this period. In addition to changes in ice dynamics, there has been a reduction in SMB of up to  $0.80 \text{ m yr}^{-1}$  water equivalent between 2013 and 2015 (Figure S4) with respect to a 1979–2005 baseline, particularly near the grounding line. This suggests that increases in mass loss in the region are driven by both surface processes and ice dynamics.



Due to the length of the Getz Ice Shelf grounding line (~880 km), even small changes in its position can have a major impact on mass balance estimates. As an example, a uniform modest grounding line retreat of 100 m would result in an ~36 Gt ice mass loss for the region (using CryoSat-2 ice thickness values at the grounding line). Note that this is not equivalent to the sea level contribution as much of this ice is grounded below sea level. Gravimetry is the only technique able to directly measure mass changes attributable to changes in grounding line position (as it only measures mass changes occurring above flotation) [Bouman *et al.*, 2014]. Therefore, the more negative imbalance estimates from gravimetry compared to other mass balance methods, coupled with the ice dynamic changes since 2008, strongly suggest grounding line retreat. Without detailed knowledge of grounding line motion, it is difficult to perform an accurate contemporary assessment using the IOM approach or from  $dh/dt$ . This highlights the importance of accurate, time-dependent, grounding line data for both IOM and volume change approaches for ice sheet mass balance.

## 5. Conclusions

We use CS2 to reassess IOM mass balance for the Getz and Abbot regions, where uncertainties in ERS-1-derived ice thickness measurements were thought to be a major source of discrepancy. The potential for CS2 to accurately calculate grounding line flux is demonstrated for basins draining into the Amery Ice Shelf, with calculations using CS2 ice thicknesses showing excellent agreement with those based on IPR data.

We use the new thickness measurements to give a 2006–2008 revised mass balance of  $8 \pm 6 \text{ Gt yr}^{-1}$  for glaciers draining into the Abbot Ice Shelf, providing agreement with other geodetic techniques. Additionally, the mass budget results presented here show excellent agreement with data inversion results from the RATES project, using the same drainage basin extents. This agreement suggests that the Abbot region was close to balance for the 2006–2008 period.

Additionally, we apply the same technique over the Getz sector to re-estimate a mass balance of  $5 \pm 17 \text{ Gt yr}^{-1}$  for 2006–2008, which is at the more positive end of estimates from other techniques, most likely due to biases present in the firn air content correction used and the inability to fully account for enhanced basal melt directly at the grounding line. Since 2008 there have been negative elevation rates near the grounding line, reductions in SMB, and up 20% increases in ice velocity for the Getz sector. These trends indicate that the increase in mass imbalance is caused by both ice dynamics and surface processes. Combined with more negative results from gravimetry, we conclude that grounding line retreat in the region is likely since about 2008. This study demonstrates the ability for CS2 to better constrain future IOM mass balance estimates in regions where there is poor coverage by IPR. We find a positive bias in previous ice thickness products near the grounding line, leading to an overestimate of the outgoing flux and, consequently, a negatively biased mass balance. The improved accuracy offered by CS2 near the grounding line will also reduce the need for manual corrections to derived ice thickness measurements.

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